Building and Environment 95 (2016) 189–198

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Environmental emissions at foundation construction stage of buildings – Two case studies

Malindu Sandanayake, Guomin Zhang*, Sujeeva Setunge

School of Civil, Environmental and Chemical Engineering, RMIT University, GPO Box 2476, Melbourne VIC 3001, Australia

A R T I C L E I N F O

Article history:
Received 6 July 2015
Received in revised form
3 September 2015
Accepted 5 September 2015
Available online 9 September 2015

Keywords:
Greenhouse gas emission
Non greenhouse gas emission
Foundation
Construction
Buildings
Life cycle

A B S T R A C T

Foundation construction involves heavy machine usage which contributes to greenhouse gas (GHG) and non-GHG emissions. The study aims to develop a model to estimate and compare emissions at foundation construction and demonstrate its application using two case studies. A process-based quantitative method is established to estimate emissions due to materials, transportation, and equipment usage. The results are analysed under five impact categories including Global Warming Potential, Acidification Potential, Eutrophication Potential, Photochemical Oxidant Formation Potential and Human Toxicity Potential. Analytical Hierarchy Process is employed to obtain weighting factors to assess impact categories under global and local perspectives. Results obtained an average GHG emission of 67%, 19% and 14% from materials, equipment and transportation respectively. This observation signifies the relative higher percentage of emission distribution of equipment and transportation in foundation construction compared to that in the total building construction. Considerable amount of non-GHG emissions such as Nitrous Oxides and Carbon Monoxides were recorded. Global Warming Potential remained the most prominent impact potential from all the perspectives considered, with an overpowering 75% contribution from global perspective. However, this relative importance is reduced to 33.74%–34.85%, with a relative increase in Photochemical Oxidant Formation and Eutrophication Potentials to 32.55% and 31.92% at regional and local perspective. Therefore emissions such as Nitrogen Oxides, Carbon Monoxides and Sulphur Dioxide should be given more consideration at the regional and local perspectives. Results also convey that the emission comparison perspective could change the focus of environmental impacts considerably.

1. Introduction

Buildings account for one-sixth of the world freshwater withdrawals, one quarter of wood harvest and two fifths of its materials and energy flows [1–4], and it is one of the seven dominant sectors that contributes greatly towards environmental emissions [5]. A systematic estimation of these emissions can be the initial step towards reduction of emission impacts. Many research studies have been undertaken on life cycle environmental effects of a building with a conclusion that the use phase of a building accounts for 80–90% while the construction phase is only responsible for 0.4–12% of the total emissions [2,5–10]. These results have shown that most of the current research focus on finding new technologies and regulations in reducing emissions at use phase of the building, paying less attention to other phases of the building such as material, construction and end-of-life phase [4,6,11,12].

Guggemos et al. in their studies highlighted the importance of assessing environmental impacts at the construction stage at an aggregate level [13]. As a critical step in the construction phase, foundation construction includes typical activities such as excavation, piling, and extensive concrete works. Utilisation of heavy construction machines and equipment are necessary to accomplish these activities. Therefore, emissions due to equipment usage could be relatively higher in foundation construction compared to other stages of construction. Another fact is that these emissions are released at a much shorter time span when compared to the whole structure construction. Although it is evident that emissions at foundation construction may be significant at an aggregate level, studies have seldom concentrated on emission levels at foundation construction stage separately [10,12,14]. There can be several reasons for this negligence. Difficulty in collecting on-site data is one of the major reasons. This difficulty can be in the form of getting

---

* Corresponding author.
E-mail address: kevin.zhang@rmit.edu.au (G. Zhang).

http://dx.doi.org/10.1016/j.buildenv.2015.09.002
0360-1323/

continuous site access, obtaining construction related documents and time consuming nature in data collection. Another reason is that after completion of the building, foundation is physically hidden from the environment and therefore given less exposure to receiving public criticism. Therefore, this research focused on estimation of environmental emissions in foundation construction.

2. Past research on building emission studies and research gap

With the concern of environmental sustainability, recent research effort has been extended from traditional focuses such as life cycle cost to environmental impact brought by building activities [15–17]. Initial research findings highlighted the importance of use phase emissions in a building [3,18,19]. Therefore many past studies concentrated on emission reduction possibilities at use phase to provide improved living conditions for inhabitants [20–22]. The results of these studies clearly signify that the use phase of the building is given more attention compared to other phases of the building. However few emission studies tried to investigate the importance of emission in other phases such as construction phase, material phase and end-of-life phase [10,13,23]. These studies conclude that emissions at other phases should be given more importance at an aggregate level.

The few emission studies that concentrated on construction phase focused only on a particular emission source [12,24,25]. Table 2 summarises past emissions studies on buildings in the life cycle phases and indicates that most of the emission studies at construction phase considered material optimisation options and neglected other emission sources such as equipment usage and transportation. This can be due to lack of inventory, uniqueness of construction technique and modelling issues. Moreover, majority of these studies are directed only towards evaluation of greenhouse gases (GHG) emissions with little attention given to non-GHG emissions [12]. Nevertheless, heavy equipment usage at foundation construction can result in considerable amounts of non-GHG emissions due to partial combustion of fuel which can have adverse effects on human health even if present in smaller amounts. Thus, the study intends to evaluate both GHG and non-GHG emissions at the foundation construction stage. Methodologies for evaluation of these emissions are explained in the following section.

3. Methods

3.1. Scope and system boundary

3.1.1. Emission substances considered

Australian Greenhouse gas accounts (AGGA) factors report describes Carbon dioxide (CO_2), Nitrous Oxide (N_2O) and Methane (CH_4) emissions as major GHG emissions from stationary and mobile machines [26]. Therefore, the present study considered CO_2, N_2O and CH_4 emissions from transport vehicles and equipment usage and hereon GHG emissions refer to these three emissions.

Apart from GHG emissions, non-greenhouse gas emissions such as Carbon Monoxide (CO), Nitrogen oxide (NO_x) and particulate matter (PM) are often emitted during the fuel combustion of stationary equipment and transport vehicles [10,13,27,28]. Thus the case study considers selected non-greenhouse gas emissions that are frequently found in fuel combustion of equipment and transport vehicles. Material stage considers embodied emissions of materials. Table 1 shows the emission substances considered for each stage in construction phase.

Table 1
Emission substances considered in different stages of construction.

Stage	Emission substances included
Material stage	CO_2
Equipment usage stage	CO_2, CH_4, N_2O, CO, NOx, PM, Sulphur dioxide (SO_2)
Transportation stage	CO_2, CH_4, N_2O, CO, NO_x, Sulphur dioxide (SO_2)

3.1.2. System boundary for the study

An ideal system boundary for emissions in construction phase should include embodied emissions from materials, emissions due to machines and equipment usage, transportation of machines and equipment, transportation of labour and disposal of construction waste [12]. Although this system boundary seems to be the most accurate, some studies argue that the system boundary for the construction phase should exclude embodied emissions due to materials [10,13]. Since one of the objectives of the study is to understand the significant emission sources in the construction phase, embodied emissions of materials are also included in the study. Both the construction projects included in the case study analysis are located in central building district and therefore public transportation is used as the mode of labour transportation. The practical difficulty of tracking these emissions forced the exclusion of emissions due to labour transportation from the system boundary of the study. Thus, embodied GHG emissions of materials (E_M), emissions due to machines and equipment usage (E_{EQ}) and emissions due to transportation of materials and equipment (E_T) are considered as the emission sources for this study.

3.2. Quantitative approach selection

Based on ISO 14044, Life Cycle Assessment (LCA) is a powerful tool to evaluate environmental impacts of buildings throughout its life cycle [29]. LCA describes three distinct methods namely input–output, process based and hybrid approach that can be used to evaluate the environmental emissions of a product or process over its life cycle.

The applicability of these methods differs according the purpose of the study, assumptions and limitations and data availability. Input–output analysis is a top-down economic approach which evaluates the effects of different industry sectors considering the economy as a whole [30,31]. This method is an effective way of estimating emissions when it is difficult to obtain process specific data. Many studies have used input–output analysis to evaluate the embodied emissions of materials as it is often difficult to obtain the upstream process data. Process based analysis is a bottom-up approach to evaluate environmental emissions considering the activities in the process. This approach requires high quality data to obtain more conclusive results. If this requirement can be accomplished, a process based approach could be the best approach to evaluate emissions. Hybrid based approach is a more comprehensive analysis which uses a combination of the above two approaches. Two types of hybrid analyses are often used in emission studies on buildings, i.e., input–output based hybrid analysis and process based hybrid analysis. Process based hybrid analysis uses process data to perform the analysis and input–output data to fill in the gaps wherever there is lack of process data. On the contrary, an input–output based hybrid analysis evaluates the whole system using input–output method and the known process based results are then subtracted from the total value to obtain the missing values. These are then added to the known process based results to get the whole impacts of the process. For more comprehensive information on hybrid analysis methods refer to the works done by Treloar [32–34]. However, in case of a specific case study analysis a process based analysis is the most effective method to evaluate

Table 2
Matrix analysis of selection of different methods and life cycle phases by different LCA studies related to buildings.

Method of analysis	Material	Construction	Use and maintenance	End of life
Input-Output	[4,31,35,36]	[4,31,35,37]	[4,31,35–37]	[4,31,35,37]
Process method	[2,5,10,13,14,18,23,38–47]	[5,10,12,13,18,24,39,45,46,48,49]	[2,5,10,12–14,18,21,23,38–40,42–46,49,50]	[2,5,10,12–14,18,21,39,40,42,45,46,49]
Hybrid methods	[25,51–55]	[52–54]	[25,51,53–55]	[25,51,53]
Total studies	***28***	***18***	***32***	***21***

environmental impacts [5,12]. Table 2 shows the typical methods of analysis used in the literature for the LCA studies in different life cycle phases of buildings.

After consideration of all the advantages and limitations a process based methodology was developed to address the required scope and system boundary.

3.3. *Quantitative models used for calculating emissions*

The following quantitative equations are developed to evaluate the emission substances mentioned. Emission factors published by Inventory of Carbon and Energy (ICE), Australian National Inventory Report (AUS NIR) and United States Environmental Protection Agency (US EPA) are used to evaluate emissions from materials, transportation and equipment usage. There are several reasons for adopting US EPA emission factors to estimate non-GHG emissions from stationary equipment. The main reason is that these factors are developed based on the power of the machine while taking into account the deterioration and real emission pattern. This provides a unique emission factor for every machine which is more effective than fuel based emission factors because it reflects the practical emission pattern better. Fuel based emission factors published by Australian greenhouse gas accounts are used to evaluate GHG emissions as they are only dependent on the fuel consumption and a country specific inventory would represent actual conditions better. ICE database is used to estimate the embodied emissions from materials because it is one of the most comprehensive inventories for embodied emission factors for materials.

Total emissions for each emission substance can be measured from the equation below.

$$E_n = \sum_{i,n=1}^{5} E_{i,n} \tag{1}$$

where E_n is the total emission of the emission substance n considered and $E_{i,n}$ is the emission of nth emission substance from the ith emission source.

3.3.1. *Embodied emission calculations for materials (E_M)*

Embodied emissions of materials are measured using the following equation

$$E_M = \sum Q_i * e_{im} \tag{2}$$

where, E_M is the embodied CO_2 emission of materials (i) used in the construction phase in $kgCO_2\text{-}eq$, Q_i is the amount of ith material used in kgs and e_{im} is the energy factor or the emission factor for ith material in carbon dioxide equivalents ($kgCO_2\text{-}eq/kg$).

3.3.2. *Emissions due to transportation (E_T)*

GHG emissions due to transportation are calculated using the following equation.

$$E_{T_{1,j}} = \frac{Q_j * EC_j * EF_j}{1000} \tag{3}$$

where $E_{T1,j}$ is the GHG emissions from the fuel type (j), Q_j is the quantity of the fuel type (j) in kL, EC_j is the energy content factor for fuel type (j) in GJ/kL and EF_j is the CO_2 emission factor for the fuel type (j) in $kgCO_2\text{-}eq/GJ$.

Non-greenhouse gas emissions due to transportation ($E_{T2}\ (I)_{ijk}$) are estimated from the following equation.

$$E_{T_2}(I)_{ijk} = A_{ijk}^{u=2} * EF(I)_{ijk} \tag{4}$$

where I is non-greenhouse gases, $A^{u\ =\ 2}$ is the vehicle kilometres travelled and $EF(I)_{ijk}$ is the exhaust emission factor for gas I from vehicle type i and age class j for fuel type k in g/km. $EF(I)_{ijk}$ can be determined using the following equation.

$$EF(I)_{ijk} = \left(ZKL_{ijk} + DR_{ijk} \times CumVKT_{ijk}\right) \tag{5}$$

where ZKL_{ijk} is the emission at zero kilometre level, DR_{ijk} deterioration rate and $CumVKT$ is the cumulative distance travelled by the vehicle in km.

3.3.2.1. *Emissions due to equipment usage (E_{EQ}).*

Estimation of emissions due to equipment usage is similar to estimation of emissions due to transportation. Since CO_2 emissions only depends upon the amount of fuel consumed, it is estimated by Equation (3). Non-CO_2 emissions can be evaluated using the general equation given below.

$$E_i = EF_i * P * T * LF \tag{6}$$

where: EF_i is the emission factor for the emission element i considered in $g/(kW\text{-}hr)$; P is the rated power output of the equipment considered in kW; T is the hours of use of the equipment for the activity considered; LF is the load factor which is the fraction of available power during the operation of equipment.

A brief explanation of the methodology for emission factors calculation published by US EPA is explained below [56].

3.3.2.2. *Emission factor calculation for HC, CO, NOx.*

HC, CO and NO_x emission factors for construction equipment depend upon factors such as the age of the machine, on-site working conditions, maintenance and cumulative usage. US EPA suggests two terms, Deterioration factor (DF) and Transient adjustment factor (TAF) into the basic steady state emission factor (EF_{SS}) to incorporate these aspects into the calculation model. The following equation shows the modified emission factor for HC, CO and NO_x.

$$EF_{HC,CO,NO_x} = EF_{SS} * DF * TAF \tag{7}$$

TAF adjusts the laboratory emissions to practical emission patterns and these values can be directly obtained from the US EPA report. DF symbolises deterioration of the machine. The procedure for calculation of DF is as follows:

For Age factor = <1

$$DF = 1 + DF_{rel} * (Age\ factor)^{b} \tag{8}$$

For Age factor >1

$$DF = 1 + DF_{rel} * (Age\ factor) \tag{9}$$

Age Factor is given by,

$$Age\ factor = \frac{Cumulative\ hours * Load\ factor}{Median\ life\ at\ full\ load} \tag{10}$$

where DF_{rel} = relative deterioration factor which is a constant for a given pollutant/technology type.

For compression ignition engines (diesel fuel) the value of b is always 1. The derivation of value of DF_{rel} can be found in Appendix G of the US EPA report for emission factors for non-road modelling [56]. The value of DF_{rel} for non-road diesel engines is given in Table 3. Tier represents the technology type which is an emission standard to identify the emission level of the machine.

3.3.2.3. Emission factor calculation for PM. Emission factor for PM can be determined similarly from Equation (11) while accounting for the sulphur content of the fuel. This is because the PM emissions are directly dependent on the sulphur content present in the fuel. Therefore, the above equation can be modified as follows to determine the emission factor for PM.

$$EF_{PM} = EF_{SS} * DF * TAF * S_{PM_{adj}} \tag{11}$$

where, S_{PMadj} is the sulphur content adjustment to PM emission factor. The procedure to determine the sulphur adjustment to PM emission factor is given below.

$$S_{PM_{adj}} = BSFC * 453.6 * 7.0 * soxcnv * 0.01 * (soxbas - soxdsl) \tag{12}$$

The term soxcnv represents the fraction of diesel fuel sulphur converted to PM. This term depends upon the technology type of the machine. Soxbas is the default certification fuel sulphur weight percentage, and soxdsl is the episodic fuel sulphur weight percentage. Values of *soxbas* and *soxdsl* vary based on the types of fuel and technologies.

3.3.2.4. Emission factor calculation for SO_2.

$$EF_{SO_2} = (BSFC * 453.6 * (1 - soxcnv) - HC) * 0.01 * soxdsl * 2 \tag{13}$$

The equation encounters for corrections for the amount of sulphur converted to PM emissions directly. The value 2 is the grams of SO_2 firmed from a gram of sulphur and the other terms carry the same meaning as before.

3.4. Impact assessment

Impact analysis is the process of understanding estimated emissions in terms of the potential impacts [57] which include five typical categories, i.e., Global Warming Potential for 100 years (GWP 100), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Oxidant Formation Potential (POFP) and Human Toxicity Potential (HTP). It is associated with three distinct steps:

Step 1 – Assign environmental emissions into relevant impact categories
Step 2 – Characterise the environmental emissions in the selected impact categories
Step 3– Compare results between different perspectives by applying suitable weighting criteria

A systematic methodology for comparing these emissions is suggested by Hermann et al. by combining life cycle assessment, multi-criteria analysis and environmental performance [58]. The environmental emissions are categorised into the concerned impact categories by multiplying the corresponding characterisation factors in Table 4. The obtained characterised potential impacts (P_i) are then normalised by dividing by a normalisation factor (N). Normalisation factors for Australia are obtained from the Life cycle impact assessment method report [59]. A suitable weighting factor (Wi,j) is applied to the normalised impacts to obtain a single index ($I_{i,j}$) which can be used as a comparative tool.

Table 3
Relative deterioration factors (DF_{rel}) for different emission substances according to the technology.

Pollutant substance	Tier 0	Tier 1	Tier 2	Tier 3
HC	0.047	0.036	0.034	0.027
CO	0.185	0.101	0.101	0.151
NOx	0.024	0.024	0.009	0.008
PM	0.473	0.473	0.473	0.473

3.4.1. Calculation of weighting factors for impacts using Analytical Hierarchy Process

The importance of impact values calculated in impact assessment can be different for various conditions. Also, the importance of impact categories can be different based on global, regional and local perspectives which consider the geographical locations. Global perspective considers the effect of environmental impacts on global environment whereas regional and local perspective considers effect on a region and local environment. Therefore it is required to calculate a relevant weighting factor which represents these three perspectives accurately. Analytical Hierarchy Process (AHP) is a decision making tool which could be effectively used to ascertain weights for different perspectives [60]. Pairwise comparison is an effective method in AHP to determine the relevant importance of intended criteria. Expert opinions are collected using surveys to identify the relative importance of each impact category from the three perspectives. The responses are collected based on 1 to 5 likert scales with 1 representing not important and 5 representing extremely important. Out of the 20 invitations sent, 12 completed responses were collected. The collected results are then used to develop a 5 x 5 matrix using pairwise comparison. Each cell value shown in Table 5 is then divided by the column total and number of impact elements (i) to obtain the corresponding weights for all the impact categories for the three perspectives using pairwise comparison of AHP process [61].

To check the consistency of the obtained relative important factors a consistency index (C.I.) is introduced. C.I. can be obtained using the following steps. First step is to multiply the column totals for each impact by the calculated relative weights ($W_{i,j}$) and then add them together to get the total as shown in Table 5. The next step is to subtract the number of impacts from the obtained total. C.I. is then obtained by dividing this total by the number of impacts less one. If the acquired C.I. is less than the tolerance level of 10% then it can be concluded that the collected opinions are consistent.

$(C.I.)_{global} = (5.09-5)/(5-1) = 2.27\% < 10\%$ tolerance level index.

$(C.I.)_{local} = (5.08-5)/(5-1) = 1.96\% < 10\%$ tolerance level index.

Both C.I. values are less than the tolerance level of 10% and therefore can be implied that the obtained expert judgements are consistent.

Table 4
Characterisation factors for the environmental impact potentials considered.

	GWP (CO_2eq)	AP (SO_2eq)	EP (PO_4^{3-} eq)	POFP (C_2H_4 eq)	HTP ($C_6H_4Cl_2$ eq)
HC	23	–	–	1	–
CO	–	–	–	0.3	–
CO_2	1	–	–	–	–
NOx	–	0.5	0.13	–	1.2
PM	–	–	–	–	0.84
SO_2	–	1.2	–	0.5	0.1
NMVOC	–	–	–	1	–

Table 5
Matrix of weighting factors for the impact categories considered from AHP.

J = global	GWP	AP	EP	POFP	HTP	$W_{i,j}$	$W_{i,j}*Total$
GWP	1.00	2.90	2.93	2.28	4.00	**0.41**	0.98
AP	0.34	1.00	1.58	1.25	1.73	**0.18**	1.06
EP	0.34	0.63	1.00	0.43	0.83	**0.10**	0.95
POFP	0.44	0.80	2.31	1.00	2.41	**0.20**	1.08
HTP	0.25	0.58	1.21	0.42	1.00	**0.10**	1.03
Total	***2.37***	***5.91***	***9.04***	***5.38***	***9.97***	***1.00***	**5.09**
J = regional	GWP	AP	EP	POFP	HTP	$W_{i,j}$	$W_{i,j}*Total$
GWP	1.00	0.38	0.52	0.50	0.60	**0.11**	1.00
AP	2.64	1.00	0.47	1.00	1.58	**0.21**	1.09
EP	1.93	2.13	1.00	1.65	2.45	**0.33**	0.99
POFP	2.02	1.00	0.61	1.00	1.58	**0.21**	1.00
HTP	1.67	0.63	0.41	0.63	1.00	**0.14**	1.02
Total	***9.26***	***5.14***	***3.00***	***4.78***	***7.20***	***1.00***	***5.14***
J = local	GWP	AP	EP	POFP	HTP	$W_{i,j}$	$W_{i,j}*Total$
GWP	1.00	0.47	0.50	0.34	0.36	**0.09**	0.96
AP	2.13	1.00	1.00	0.38	0.44	**0.15**	1.07
EP	1.99	1.00	1.00	0.47	0.35	**0.14**	1.06
POFP	2.93	2.61	2.13	1.00	0.82	**0.30**	1.01
HTP	2.78	2.26	2.90	1.22	1.00	**0.33**	0.98
Total	***10.82***	***7.34***	***7.53***	***3.42***	***2.96***	***1.00***	**5.08**

4. Case studies

Two case studies (A and B) on foundation construction of high-rise buildings are considered for the analysis. Case studies are named as A and B in order to maintain the commercial sensitivity of the projects. Fig. 1 shows an overview of both the construction sites. Case study A is a high-rise residential building with bored pile foundation which comprises of 134 piles out of which 84 are surrounding piles along the perimeter. The depth of a pile is around 20–22 m. The water table is well below the designed depth of the pile. A capping beam of size varying from 480 to 1000 mm width to 500–1300 mm depth is placed to connect all the surrounding 84 piles. Case study B is also a high-rise residential building with raft foundation. Apart from the raft, some piles and pad footings are employed at the foundation level. The building characteristics of the two case studies are shown in Table 6. A leading building contractor worked as the main contractor while a pioneer in earthworks was employed for foundation construction. The two case studies were selected for comparison of emissions at different foundation construction. Since the same contractors were employed at both the sites it can be assumed that management skills and construction performance are almost the same. According to the mathematical models explained in methodology, several site specific data, machine and vehicle specific data were required. Thus, three different methods of data collection were used to obtain the required data for estimation of emissions from materials, equipment usage and transportation.

A generic figure showing the major activities related to environmental emissions in foundation construction is shown in Fig. 2. Some of the activities are not included in the case studies due to project specific issues and limitations.

4.1. Data collection on materials

Concrete and reinforcement steel are the two major materials used for foundation construction. Apart from that formwork was used as a material. Other materials such as sand and cement used for backfilling are not considered as they are used in minor quantities. Quantities of each material used are required to estimate embodied emissions of materials. These data were obtained from the daily receiving logs from the manufacturers. The major quantities of materials used in two case studies are shown in Table 7.

4.2. Data collection on transportation

Estimation of emissions due to transportation requires the distance from the distribution plant to the construction site and the cumulative kilometres travelled by the vehicle. Distance travelled

Construction site for case study A

Construction site for case study B

Fig. 1. Overview of the two construction sites.

Table 6
General details of the two construction projects.

Study	Total foundation area (m^2)	Floors	Project type	Floor height (m)	Foundation type	Local environment
A	6100	48	Residential	3.3	Bored-pile	Urban
B	3540	52	Residential	3.3	Raft	Urban

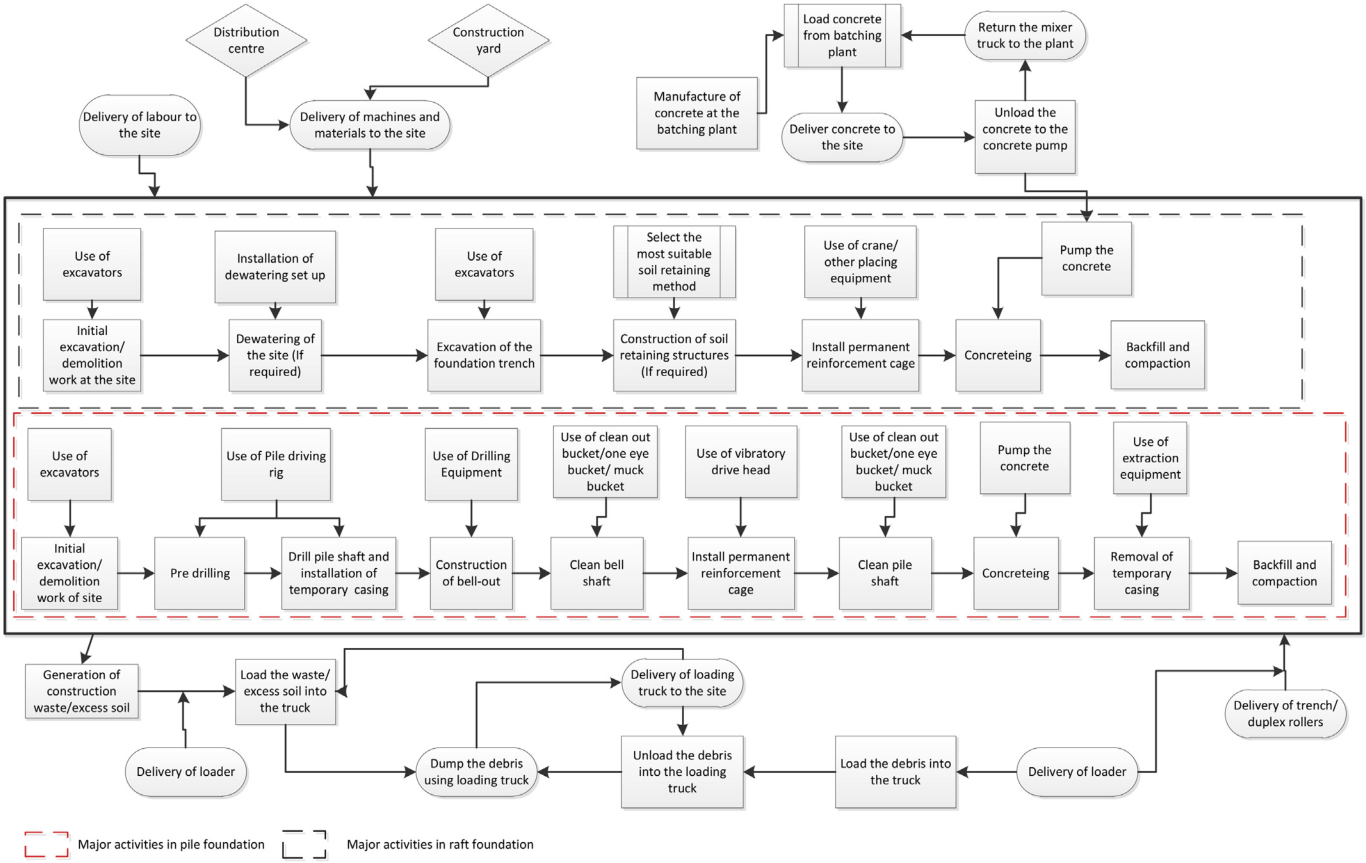

Fig. 2. Generic layout showing the major activities related to environmental emissions in foundation construction.

was determined by calculating the road map distance between the two destinations. Cumulative distance travelled is obtained from the vehicle driver. One-way transportation distances for transporting concrete and steel are shown in Table 7.

Transportation distances represent the distances between the construction site and the distribution plants of steel and concrete. The construction site is in the Central Business District (CBD) area and therefore long transportation distances are recorded. Apart from concrete and reinforcement steel, excavated soil needs to transported and dumped. The amount of excavated soil is obtained from the bill of quantity (BOQ). The volume of the soil loaded to the truck is calculated by multiplying the excavator bucket volume and the number of buckets. It is assumed that all the trucks are loaded with same amount of soil and all the soil are dumped by the same type of truck. The soil dumping site was located 10 km from the construction site. An average one way transportation of 40 km was used for concrete transportation and 30 km was used for steel reinforcement transportation to neutralize the emission variation due to transportation distance.

4.3. *Data collection on equipment usage*

Fuel combustion details are required to estimate GHG emissions due to machines and equipment usage. To estimate the non-GHG emissions from machines, more detailed data such as hours of operation of equipment and machine characteristics are required. Data on hours of operation of equipment were recorded on-site and the machine characteristics were obtained from technical

Table 7
Material quantities used.

Material	Material amounts in tonnes		One-way transportation distances (km)		
	Case study A	Case study B	Case study A	Case study B	Average
Concrete	4962.57	4468.3	50	31	40
Reinforcement Steel	132.42	102.43	35	23	30

Table 8
Characteristics of machines used in case study A.

Machine type	ID	Power (hp)	Tier	Usage (hours)	Purpose of use
Piling rig	P 1	440	3	278	Excavation of piles
Concrete truck	CT 1	565	3	221	Pumping concrete
Crawler crane	CR 1	285	3	488	Lifting & moving works
Excavator	EX 1	271	3	298	Excavation & loading works
Excavator	EX 2	349	3	604	Excavation works
Excavator	EX 3	39	4	230	Excavation works

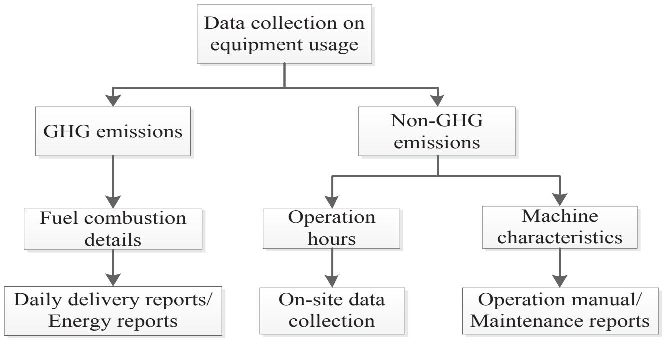

Fig. 3. Data collection methods on equipment usage.

specification sheets.

4.3.1. *Equipment used in case study A*

A detailed description of the machines and equipment used for foundation construction in case study A is shown in Table 8. A heavy piling rig was used to dig the pile hole. Auger blade was used to excavate the soil. EX 1 was mainly used for removal of excavated soil from the piles. EX 3 was used for smaller excavations inside the excavation pit. Data collection methods on equipment usage is shown in Fig. 3.

4.3.2. *Equipment used in case study B*

A detailed description of the machines and equipment used for foundation construction in case study B is shown in Table 9. Four excavators were used on-site and EX 7 was used for both loading works and excavation works while other excavators were mainly used for excavation works. Crawler crane was used for lifting works such as smaller machines and pile cages. Concrete was delivered to fulfil the existing requirement at site. The concrete was poured immediately after delivery.

4.4. *Application of methodology*

All data collected from case studies A and B are then employed in a systematic calculation process as shown in Fig. 4. Data collected for both case studies are then used in the mathematical equations to calculate the different types of emissions mentioned in Fig. 4. These emissions values are utilised to compute impacts for different impact categories. AHP process is then used to combine these impact categories from three different perspectives to understand the relative importance globally, regionally and locally.

5. Results and discussions

5.1. *GHG emissions from the two case studies*

A 261.64 and a 277.50 kg per m^2 of GHG emissions are recorded for case study A and B respectively. This is obtained by dividing the total GHG emissions at foundation construction stage shown in Table 10 by the total foundation area. Total foundation includes the basement area and ground plan area. Use of foundation area instead of the total gross floor is justified because the work at foundation level corresponds only to the foundation area of the building [62]. These values seem to be insignificant to that of the total building construction emissions. An average distribution of 66%, 19% and 15% were recorded for material, equipment usage and transportation stages respectively at foundation construction stage. GHG emission distributions for both the case studies are shown in Fig. 5.

The obtained case study results are compared with another study in order to compare the emission distribution with the emission pattern of a total building construction. The comparative study is a building construction project in China which was undertaken on conventional and pre-fabrication construction methods [5]. The comparative results in Table 10 illustrate that the percentage of emissions due to equipment usage for the foundation construction is increased almost 4 times than that for the total building construction. The prolonged machine usage for activities such as drilling, excavation and material loading could be the major reason for this upturn. Therefore, more attention should be paid to these equipment emissions at foundation construction stage considering its adverse health and environmental effects at a shorter span of time.

On the other hand, although fewer quantities of materials are involved, it was observed that material emissions govern emission distribution profiles for both the case studies. Although there is no significant improvement in emissions due to transportation, a small increase is recorded. One possible reason could be that longer wait time for concrete trucks at the site due to site delays. It was also observed that these trucks were often faced by heavy traffic jams as the site was in a densely populated area. A relative high amount of soil transportation at foundation stage could be another reason for this increase. Previous studies have shown that shorter transportation distances can reduce GHG emissions by up to 3.5% of the total emissions [5]. Although the reasons mentioned here are highly project specific, it is always recommended to plan the work in order to minimize the emissions as much as possible.

5.2. *Non-GHG emissions from the two case studies*

The results in Table 11 show that CO and NO_x are dominant among non-GHG emissions. This may be because of the partial combustion of fuel due to extended equipment usage and larger transportation impacts. However, other emission substances such as SO_2 and non-methane volatile organic compounds (NMVOC) cannot be neglected since smaller amounts of these substances could cause greater health and environmental effects. Therefore a common comparative tool similar to the comparative index ($I_{i,j}$) explained before could be effectively used in identifying the relative importance of each emission substance.

5.3. *Impact analysis*

The obtained results in the preceding section are multiplied with the characterisation factors in Table 4 to obtain the potential

Table 9
Characteristics of machines used in case study B.

Machine type	ID	Power (hp)	Tier	Usage (hours)	Purpose of use
Excavator	EX 4	184	3	512	Excavation works
Excavator	EX 5	93	3	405	Excavation works
Excavator	EX 6	47.6	4	320	Excavation works
Excavator	EX 7	271	3	485	Excavation & loading works
Crawler crane	CR 2	428	2	415	Lifting & moving works
Concrete truck	CT 2	565	3	201	Pumping concrete
Piling rig	P 2	325	3	88	Excavation of piles

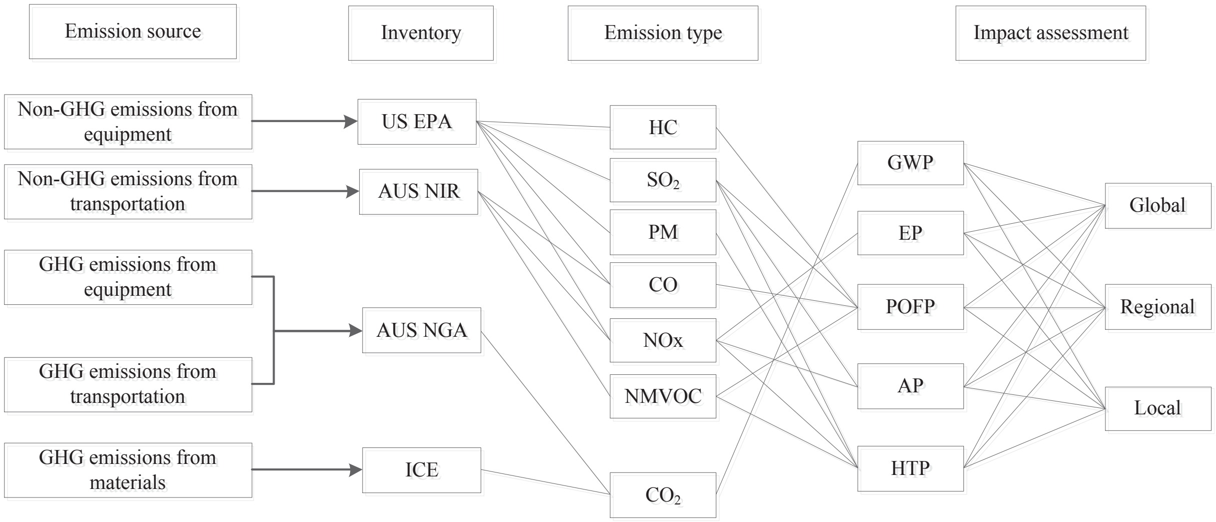

Fig. 4. A systematic calculation process for the study.

Table 10
CO_2 emission (in metric tons) comparison: foundation vs. total building construction.

Emission source	Case study A(Pile)		Case study B (Raft)		Comparative study [5]	
Material	1057.78	67%	662.38	67%	63,985	85%
Equipment usage	289.05	18%	184.61	19%	3479	4.7%
Transportation	249.14	15%	135.35	14%	7741	10.3%
Total	1595.97	100%	982.34	100%	75205	100%

Table 11
Total non-GHG emissions from both case studies.

Case study	HC (kg)	CO (kg)	NO_x (kg)	PM (kg)	SO_2 (kg)	NMVOC (kg)
Case study A	87.08	2284.20	2553.60	106.93	208.65	632.70
Case study B	60.30	1347.16	1585.91	60.57	146.56	341.66

impacts (P_i) values as shown in Table 12. These potential impacts are normalised by using the corresponding normalisation factors for each impact category [58]. The normalised impacts (P_i/N) are multiplied by the corresponding weighting factors calculated before to compare the impacts from the desired perspective. The resulting indices for both case studies are shown in Fig. 5. The overall perspective represents the condition without applying weighting factors. It is seen that in all the cases GWP remains the most dominant impact category regardless of the comparative perspective. However, the overpowering contribution of around 75% of GWP seems to be reduced to 33.74% and 34.85% respectively at the regional and the local perspectives with relatively higher contributions from POFP and EP. HTP remains insignificant from all the perspectives considered. HC, NO_x, CO, SO_2 and NMVOC contribute directly to POFP and EP impact potentials. Fig. 6 further

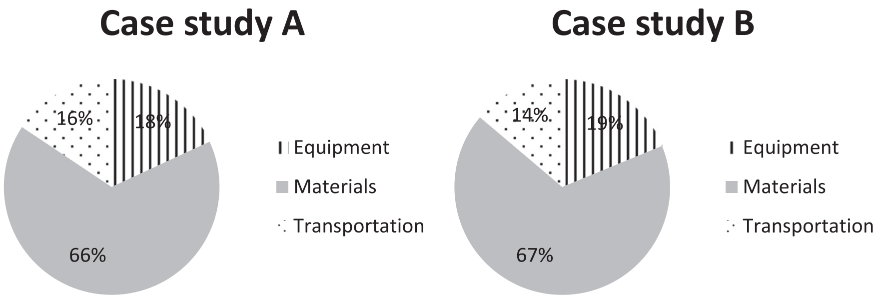

Fig. 5. GHG emission distributions for both case studies.

Table 12
Normalised potential impacts (P_i/N) calculation for the two case studies.

Impact category	Pile foundation			Raft foundation		
	(P_i)	N	P_i/N (Unit less)	(P_i)	N	P_i/N (Unit less)
GWP	1,595,975.26	6.21E+11	2.57E-06	982,339.29	6.21E+11	1.58E-06
AP	1527.18	2.67E+09	5.72E-07	968.83	2.67E+09	3.63E-07
EP	331.96	4.16E+08	7.98E-07	206.17	4.16E+08	4.96E-07
POFP	1509.363	1.61E+09	9.37E-07	537.73	1.61E+09	3.34E-07
HTP	3579.94	6.96E+10	5.14E-08	1968.63	6.96E+10	2.83E-08

highlights that POFP and EP contribute more at the regional and local perspectives respectively.

6. Conclusions and suggestions

The foundation construction process emits GHG and non-GHG emissions. The study compares emissions in the construction of two foundation types, i.e., pile foundation and raft foundation. Emissions from materials, equipment usage and transportation are considered as emission sources. A process based quantitative model is used to calculate the emissions and the comparative results are analysed to disclose the significant characteristics of emissions at the foundation construction stage.

Total GHG emissions for case study A and B are 1596 tonnes (261.64 kg/m^2) and 982 tonnes (277.5 kg/m^2) respectively. Materials, equipment usage and transportation contribute to an average GHG emission of 67%, 19% and 14% of the total emission at the foundation construction stage. This distribution at the foundation stage illustrates a significant difference to the emissions at the total building construction, with much higher contribution of emissions coming from equipment usage and transportation. Therefore, at the foundation construction, emission reduction approaches should be focusing more on equipment usage and transportation stages by careful selection of machines and equipment.

It was also found that the relative contributions of the impact categories change significantly from the global perspective to the local perspective. The results indicate that GWP 100 (100 years) impact potential which is mainly due to GHG emissions seems to be overwhelmingly high compared to other impact categories at the global perspective. However, this overpowering contribution of 75% seems to be reduced to 33% and 34% at the regional and local perspectives with relatively higher contributions coming from POFP and EP. EP contribution at the regional level is increased to 31.92% while POFP contribution is increased to 32.55% at the local level. Thus emission substances such as CO, NO_x NMVOC and SO_2 which contribute to POFP and EP should be given more consideration in the shorter run at the regional and local perspectives. Therefore, it is important to consider the emission comparison perspective in an emission study to effectively conclude the significance of each emission substance. However, the research study embraces certain limitations and assumptions to achieve the objectives. One major assumption is that the study only considers emissions related to construction work and neglects indirect emissions due to lighting, heating and cooling. Moreover, the results obtained are highly site specific and do not consider local environmental features. Contractors' ability to plan resources, site conditions, delays and construction technique are some of the major factors that can affect the emission distribution.

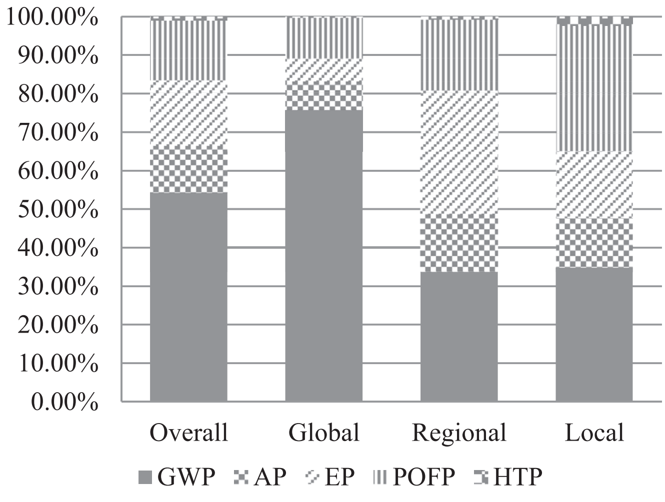

Fig. 6. Relative importance of impacts based on the three perspectives.

The results obtained in the case studies will be utilised to carry out further research on emissions at total building construction stage. It is also intended to further investigate emission reduction options at the construction stage. Further studies and research are encouraged to explore an optimum mechanism to select machines, materials and vehicles to minimize both the GHG and non-GHG emissions.

References

[1] A.A. Guggemos, A. Horvath, Comparison of environmental effects of steel-and concrete-framed buildings, J. Infrastruct. Syst. 11 (2) (2005) 93–101.
[2] C.K. Chau, et al., Assessment of CO2 emissions reduction in high-rise concrete office buildings using different material use options, Resour. Conserv. Recycl. 61 (0) (2012) 22–34.
[3] I. Sartori, A.G. Hestnes, Energy use in the life cycle of conventional and low-energy buildings: A review article, Energy Build. 39 (3) (2007) 249–257.
[4] S. Seo, Y. Hwang, Estimation of CO2 emissions in life cycle of residential buildings, J. Constr. Eng. Manag. 127 (5) (2001) 414–418.
[5] C. Mao, et al., Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: two case studies of residential projects, Energy Build. 66 (0) (2013) 165–176.
[6] G. Zheng, et al., Application of life cycle assessment (LCA) and extenics theory for building energy conservation assessment, Energy 34 (11) (2009) 1870–1879.
[7] J. Goggins, T. Keane, A. Kelly, The assessment of embodied energy in typical reinforced concrete building structures in Ireland, Energy Build. 42 (5) (2010) 735–744.
[8] M. Wallhagen, M. Glaumann, T. Malmqvist, Basic building life cycle calculations to decrease contribution to climate change – case study on an office building in Sweden, Build. Environ. 46 (10) (2011) 1863–1871.
[9] J. Nässén, et al., Direct and indirect energy use and carbon emissions in the production phase of buildings: an input–output analysis, Energy 32 (9) (2007) 1593–1602.
[10] A.A. Guggemos, Environmental Impacts of On-Site Construction Processes: Focus on Structural Frames, University of California, Berkeley, 2003.
[11] M. Suzuki, T. Oka, Estimation of life cycle energy consumption and CO2 emission of office buildings in Japan, Energy Build. 28 (1) (1998) 33–41.
[12] H. Yan, et al., Greenhouse gas emissions in building construction: a case study of One Peking in Hong Kong, Build. Environ. 45 (4) (2010) 949–955.
[13] A.A. Guggemos, A. Horvath, Decision-support tool for assessing the environmental effects of constructing commercial buildings, J. Archit. Eng. 12 (4) (2006) 187–195.
[14] S. Xing, Z. Xu, G. Jun, Inventory analysis of LCA on steel- and concrete-construction office buildings, Energy Build. 40 (7) (2008) 1188–1193.
[15] M.M. Matar, M.E. Georgy, M.E. Ibrahim, Sustainable construction

management: introduction of the operational context space (OCS), Constr. Manag. Econ. 26 (3) (2008) 261–275.
[16] P. Graham, Building Ecology: First Principles for a Sustainable Built Environment, John Wiley & Sons, 2009.
[17] J.W. Thompson, K. Sorvig, Sustainable Landscape Construction: a Guide to Green Building Outdoors, Island Press, 2007.
[18] S. Junnila, A. Horvath, Life-cycle environmental effects of an office building, J. Infrastruct. Syst. 9 (4) (2003) 157–166.
[19] T. Malmqvist, et al., Life cycle assessment in buildings: the ENSLIC simplified method and guidelines, Energy 36 (4) (2011) 1900–1907.
[20] E.A. Bergstrom, Energy use and emissions reduction strategies for structural steel fabricators: a case study, in: Department of Construction Management, Colorado State University, 2010.
[21] D.W. Yu, H.W. Tan, Y.J. Ruan, A future bamboo-structure residential building prototype in China: life cycle assessment of energy use and carbon emission, Energy Build. 43 (10) (2011) 2638–2646.
[22] M. Ruth, Technology change in US iron and steel production: implications for material and energy use, and CO2 emissions, Resour. Policy 21 (3) (1995) 199–214.
[23] S. Junnila, A. Horvath, A. Guggemos, Life-cycle assessment of office buildings in Europe and the United States, J. Infrastruct. Syst. 12 (1) (2006) 10–17.
[24] G. Gerilla, K. Teknomo, K. Hokao, An environmental assessment of wood and steel reinforced concrete housing construction, Build. Environ. 42 (7) (2007) 2778–2784.
[25] M.Y. Han, et al., Embodied energy consumption of building construction engineering: case study in E-town, Beijing, Energy Build. 64 (2013) 62–72.
[26] AGGA, Australian National Greenhouse Gas Accounts, 2013. Available from: http://www.climatechange.gov.au/.
[27] W. Rasdorf, et al., Field procedures for real-world measurements of emissions from diesel construction vehicles, J. Infrastruct. Syst. 16 (3) (2010) 216–225.
[28] S. Abolhasani, et al., Real-world in-use activity, fuel use, and emissions for nonroad construction vehicles: a case study for excavators, J. Air Waste Manag. Assoc. 58 (8) (2008) 1033–1046.
[29] ISO14044, Environmental Management — Life Cycle Assessment — Requirements and Guidelines, 2006. ISO140444.
[30] D. Hawdon, P. Pearson, Input–output simulations of energy, environment, economy interactions in the UK, Energy Econ. 17 (1) (1995) 73–86.
[31] B. Su, et al., Input–output analysis of CO2 emissions embodied in trade: the effects of sector aggregation, Energy Econ. 32 (1) (2010) 166–175.
[32] G. Treloar, et al., A hybrid life cycle assessment method for construction, Constr. Manag. Econ. 18 (1) (2000) 5–9.
[33] G.J. Treloar, et al., A hybrid life cycle assessment method for construction, Constr. Manag. Econ. 18 (1) (2000) 5–9.
[34] G.J. Treloar, Extracting embodied energy paths from input–output tables: towards an input–output-based hybrid energy analysis method, Econ. Syst. Res. 9 (4) (1997) 375–391.
[35] G.Q. Chen, B. Zhang, Greenhouse gas emissions in China 2007: inventory and input–output analysis, Energy Policy 38 (10) (2010) 6180–6193.
[36] R. Kok, R.M.J. Benders, H.C. Moll, Measuring the environmental load of household consumption using some methods based on input–output energy analysis: a comparison of methods and a discussion of results, Energy Policy 34 (17) (2006) 2744–2761.
[37] G.Q. Chen, et al., Low-carbon building assessment and multi-scale input-output analysis, Commun. Nonlinear Sci. Numer. Simul. 16 (1) (2011) 583–595.
[38] Y.G. Yohanis, B. Norton, Life-cycle operational and embodied energy for a generic single-storey office building in the UK, Energy 27 (1) (2002) 77–92.
[39] S. Citherlet, Towards the Holistic Assessment of Building Performance Based on an Integrated Simulation Approach, Citeseer, 2001.
[40] G.J. Treloar, et al., An analysis of factors influencing waste minimisation and use of recycled materials for the construction of residential buildings, Manag. Environ. Qual. Int. J. 14 (1) (2003) 134–145.
[41] N. Huberman, D. Pearlmutter, A life-cycle energy analysis of building materials in the Negev desert, Energy Build. 40 (5) (2008) 837–848.
[42] G. Verbeeck, H. Hens, Life cycle inventory of buildings: a calculation method, Build. Environ. 45 (4) (2010) 1037–1041.
[43] J. Monahan, J.C. Powell, An embodied carbon and energy analysis of modern methods of construction in housing a case study using a lifecycle assessment framework, Energy Build. 43 (1) (2011) 179–188.
[44] C.K. Chau, et al., Environmental impacts of building materials and building services components for commercial buildings in Hong Kong, J. Clean. Prod. 15 (18) (2007) 1840–1851.
[45] H.W. Kua, C.L. Wong, Analysing the life cycle greenhouse gas emission and energy consumption of a multi-storied commercial building in Singapore from an extended system boundary perspective, Energy Build. 51 (0) (2012) 6–14.
[46] B. Rossi, et al., Life-cycle assessment of residential buildings in three different European locations, basic tool, Build. Environ. 51 (2012) 395–401.
[47] I. Zabalza Bribián, A. Valero Capilla, A. Aranda Usón, Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential, Build. Environ. 46 (5) (2011) 1133–1140.
[48] Y. Chen, Y. Zhu, Analysis of Environmental Impacts in the Construction Phase of Concrete Frame Buildings, China: Department of Construction Management, Tsinghua University, 2008.
[49] X. Li, Y. Zhu, Z. Zhang, An LCA-based environmental impact assessment model for construction processes, Build. Environ. 45 (3) (2010) 766–775.
[50] J. Kneifel, Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings, Energy Build. 42 (3) (2010) 333–340.
[51] R. Fay, G. Treloar, U. Iyer-Raniga, Life-cycle energy analysis of buildings: a case study, Build. Res. Inf. 28 (1) (2000) 31–41.
[52] Y. Chang, R.J. Ries, S. Lei, The embodied energy and emissions of a high-rise education building: a quantification using process-based hybrid life cycle inventory model, Energy Build. 55 (0) (2012) 790–798.
[53] R.H. Crawford, I. Czerniakowski, R.J. Fuller, A comprehensive framework for assessing the life-cycle energy of building construction assemblies, Archit. Sci. Rev. 53 (3) (2010) 288–296.
[54] R.H. Crawford, Validation of a hybrid life-cycle inventory analysis method, J. Environ. Manag. 88 (3) (2008) 496–506.
[55] H. Dong, et al., Carbon footprint evaluation at industrial park level: a hybrid life cycle assessment approach, Energy Policy 57 (0) (2013) 298–307.
[56] USEPA, Crankcase Emission Factors for Non-Road Engine Modeling-Compression-Ignition, Environmental Protection Agency. Air and Radiation Office, USA, 2010. Office of Transportation and Air Quality.
[57] M. Finkbeiner, et al., The new international standards for life cycle assessment: ISO 14040 and ISO 14044, Int. J. Life Cycle Assess. 11 (2) (2006) 80–85.
[58] B. Hermann, C. Kroeze, W. Jawjit, Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators, J. Clean. Prod. 15 (18) (2007) 1787–1796.
[59] J.B.a.N. Howard, A Life Cycle Impact Assessment Method Part 2: Normalisation, Building Products Innovation Council, Australia, 2010.
[60] G.A. Mendoza, et al., Guidelines for Applying Multi-criteria Analysis to the Assessment of Criteria and Indicators, CIFOR, Bogor, Indonesia, 1999.
[61] M.I. Al Khalil, Selecting the appropriate project delivery method using AHP, Int. J. Proj. Manag. 20 (6) (2002) 469–474.
[62] P. Forsythe, G. Ding, Greenhouse Gas Emissions from Excavation on Residential Construction Sites 14 (4) (2014) 10.